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14. ABSTRACT

Combustion instabilities have been observed in nearly every major liquid rocket engine development effort, including the most recent development programs. They are caused by the coupling of the natural acoustic modes of the combustion chamber with the dynamics of the combustion heat release and can lead to catastrophic damage of the internal components of the rocket engine. Rayleigh's criterion states that combustion instabilities are driven when the pressure waves and the heat release are in phase and that the instabilities are damped when they are out of phase. Despite the simplicity of this relationship, the prediction of the occurrence of combustion instabilities has proven to be an enduring challenge because of the inherent complexities in the physics of multiphase turbulent flames. The present paper provides the Air Force Research Lab (AFRL)'s vision and strategy for combustor design tools that can predict combustion stability to help guide the development of the US's next generation liquid rocket engines.

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THE AIR FORCE RESEARCH LABORATORY
LEAD | DISCOVER | DEVELOP | DELIVER

AFRL's ALREST Physics-Based Combustion Stability Program

Dr. Venke Sankaran

Dr. Doug Talley

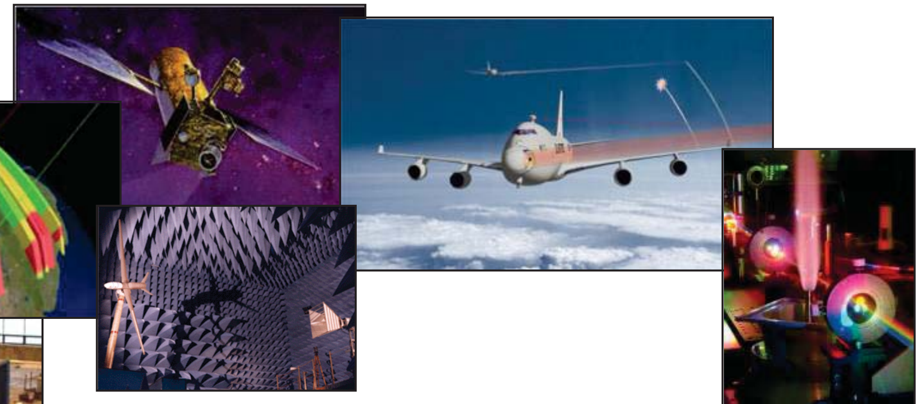
Aerospace Systems Directorate (RQ)

Air Force Research Laboratory

8 November 2012

Air Force Research Lab

Air Force Research Laboratory



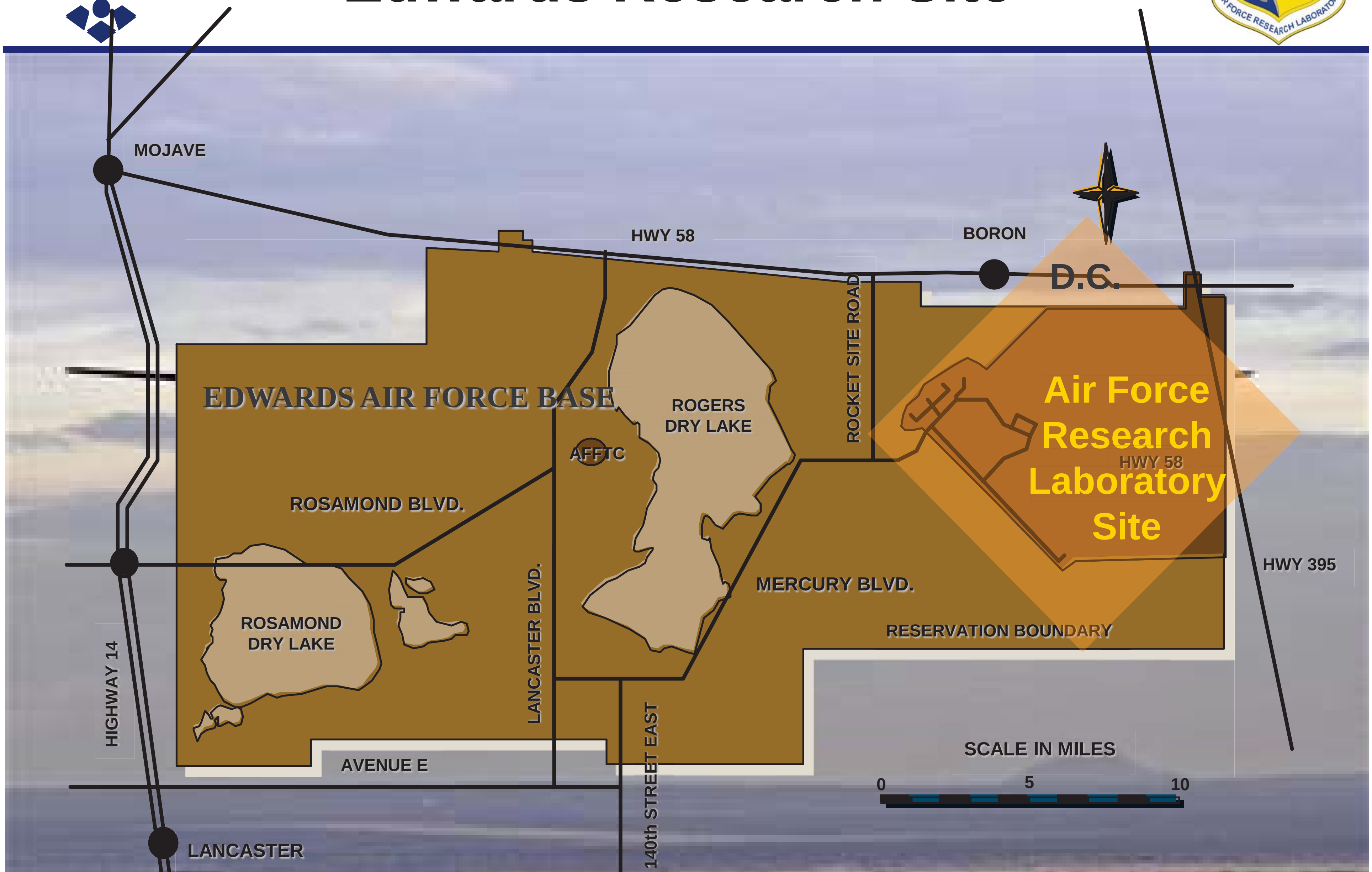
- 10 Major R&D sites across US
- 40 Locations around the World
- 10 Technical Directorates
  - Air Vehicles (RB)
  - Propulsion (RZ)

    ⬇

  - Aerospace Systems Directorate (RQ)

- 5,400 Gov't Employees
- 3,800 On-site Contractors

Edwards Research Site



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Facilities

Bench-level Labs


Altitude Facilities

- From micro-newtons to 50,000 lbs thrust

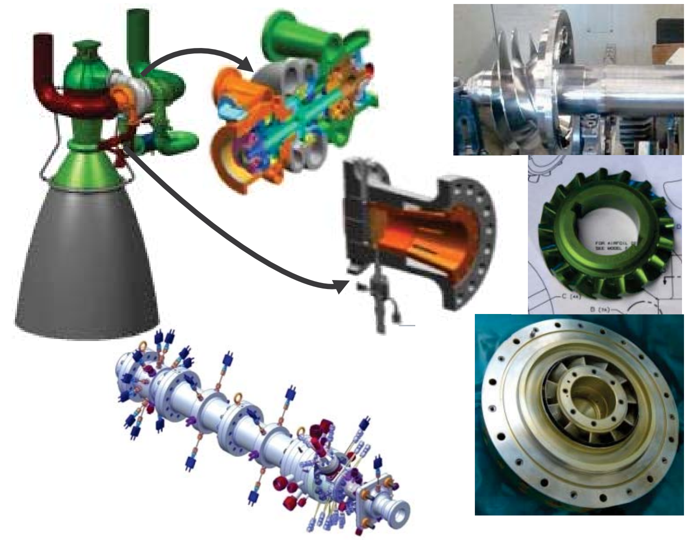
High Thrust Facilities

- 19 Liquid Engine stands, up to 8,000,000 lbs thrust
- 13 Solid Rocket Motor pads, up to 10,000,000 lbs thrust



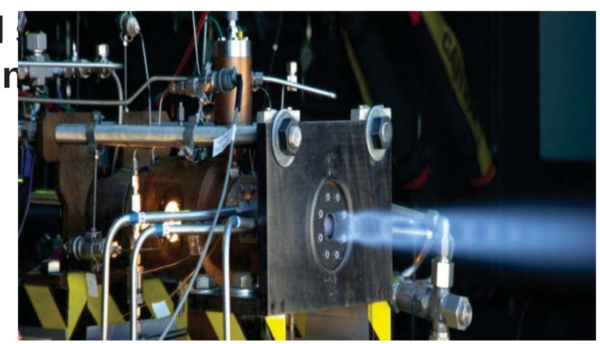
Hydrocarbon Boost

- **HCB establishes advanced, modern, domestic LRE Tech Base**
  - Required to replace Russian RD-180 on EELV
  - 1st reusable high performance U.S. HC engine
  - Establishes Ox-rich staged combustion (ORSC) tech base for U.S.
  - Help sustain ailing U.S. rocket engine industry tech development base
  - HCB strongly supports SMC/LR American Kerosene Engine project



In-House:

- Building subscale test facility to mitigate combustion devices risk
- Critical combustion research using 219 funds
- Fuel thermal
injector design



The WOWs:

- Design, build, test ORSC LOx/Kerosene Liquid Rocket Engine Tech Demonstrator
  - 250K-lbf with high Throttle Capability (SOTA is 2:1) – Enables mission flexibility
  - 100 Life Cycle with 50 cycle overhaul (SOTA is 20) – Exceeds requirement, provides margin
- ORSC is a higher performing engine resulting in a smaller launch vehicle or an increase in delivered payload

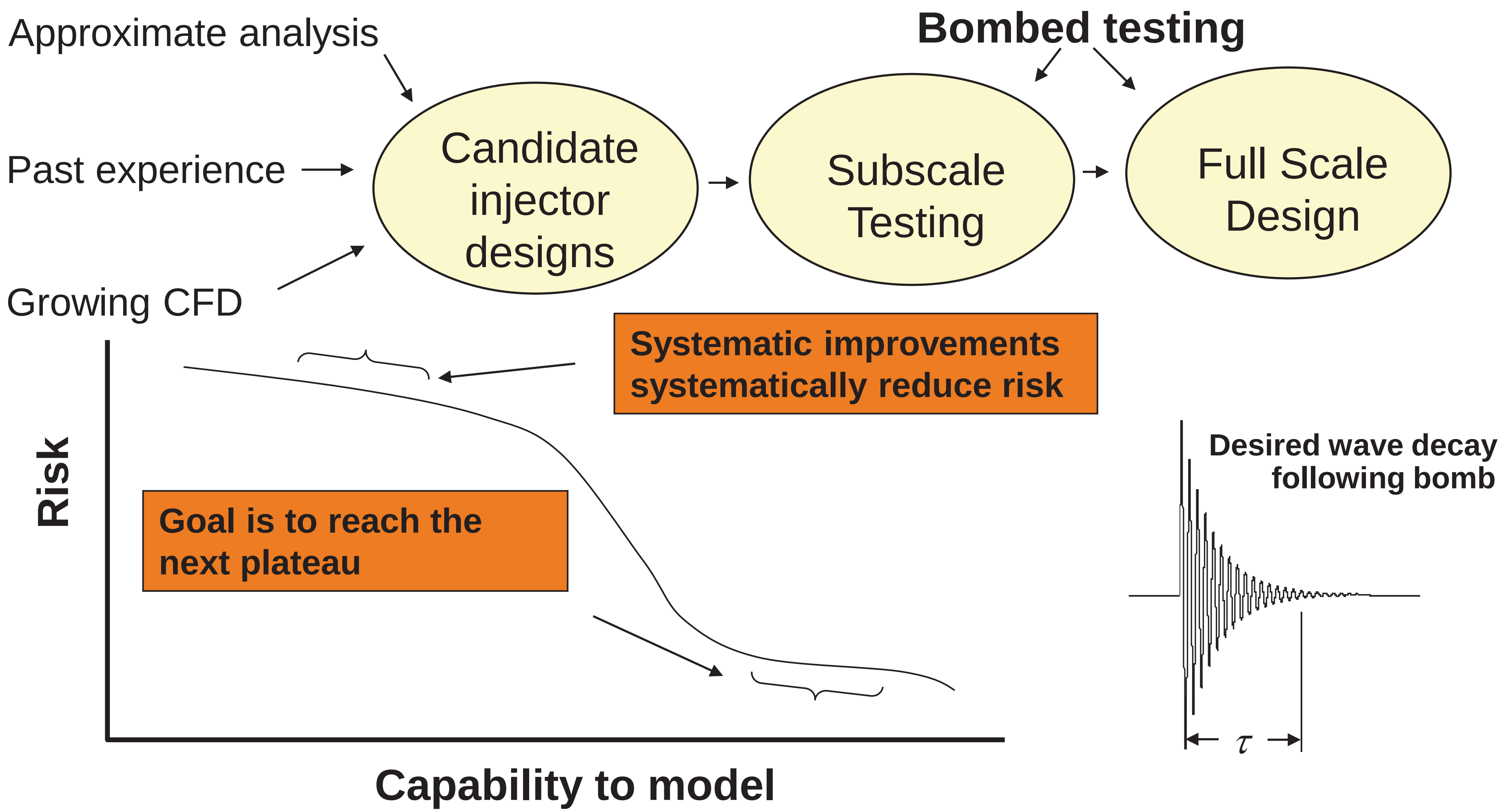
What is a Combustion Instability (CI)?

Damaged F-1 engine injector faceplate caused by combustion instability

"Combustion instabilities have been observed in almost every engine development effort, including even the most recent development programs"
– JANNAF Stability Panel Draft

- **Combustion instability is an *organized*, *oscillatory* motion in a combustion chamber *sustained by combustion*.**
- **Irreparable damage can occur in <1s.**
- **Combustion instability caused a four year delay in the development of the F-1 engine used in the Apollo program**
  - **> 2000 full scale tests**
  - **> $400 million for propellants alone (at 2010 prices)**
- **CI has been identified as a major risk factor in the HCB demo and future engine development.**

Risk Reduction



Challenges

- High pressures
  - Supercritical pressure with cryogenic propellants
  - Challenging to obtain detailed data
- Turbulence and Combustion
  - Unsteady dynamics requires LES or hydrid RANS-LES
  - Detailed mechanisms for chemical kinetics
  - Turbulent combustion closures
- Boundary Conditions
  - Simulations must include fuel-ox manifolds
- Data Processing

Overview of ALREST

(Advanced Liquid Rocket Engine Stability Technology)

OBJECTIVE

- **Develop advanced physics-based combustion stability design tools to reduce the risk of developing combustion instabilities in future Air Force liquid rocket engine development programs.**

APPROACH

- **Fully coordinate with other national efforts to conduct data-centric, multi-fidelity model development.**

Data-Centric Model Development

Anderson (Purdue)
- AFOSR
- NASA CUIP
- ALREST
- AFRL

Frederick (UAH)
- NASA CUIP
- AFRL
- ALREST

Karagozian (UCLA)
- AFOSR

Leyva, Talley (AFRL)
- AFOSR
- ALREST

Cavitt (Orbitec)
- AFRL
- ALREST

Santoro (PA State)
- AFOSR (core)
- NASA CUIP
- ALREST

Yu (Maryland)
- NASA CUIP

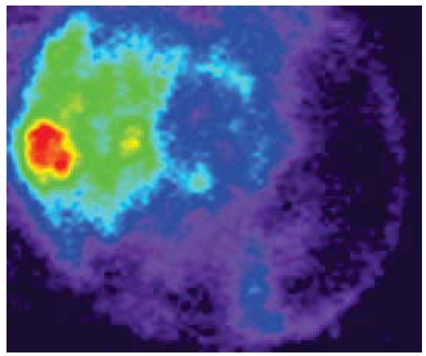
Zinn (GA Tech)
- AFOSR

Nestleroad Engin'ng
- MDA

Experiments

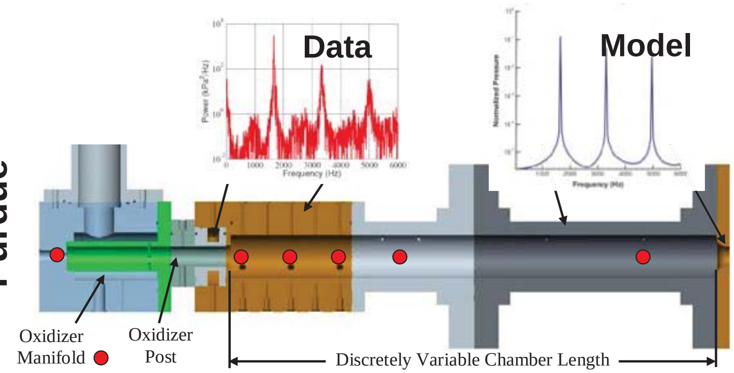
Spinning CI

GA Tech



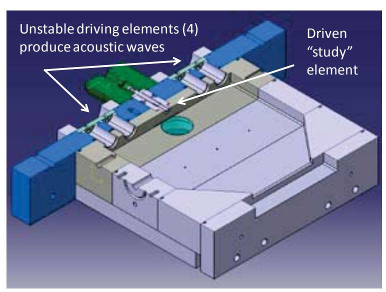
Longitudinal CI

Purdue

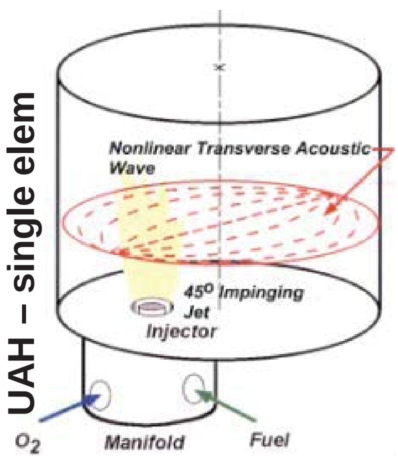


Standing CI

Purdue – multi elem

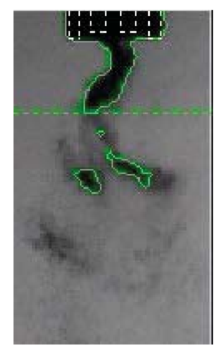


UAH – single elem

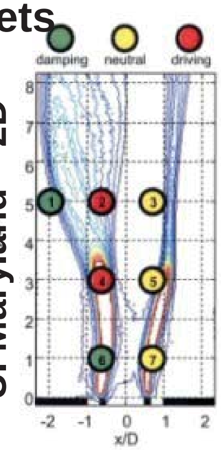


Driven jets

AFRL - coax



U. Maryland – 2D



Acoustics

HCB will be heavily instrumented to provide CI data

Full Scale (existing and HCB)

Multi-Fidelity Model Development

Flandro (GTL)
- **OSD, AFRL**

Heister (Purdue)
- **AFOSR, NASA**

Merkle (Purdue)
- NASA, AFRL, AFOSR, ALREST

Muss (Sierra)
- **AFRL**

Palaniswamy (Metacomp)
- **AFOSR, AFRL, MDA ALREST**

Yang (PA State)
- **AFOSR, AFRL, MDA**

Bellan (JPL)
- **AFOSR**
- **ALREST**

Kassoy (U. Colo.)
- **AFOSR**

Priem consultants
- **ALREST**

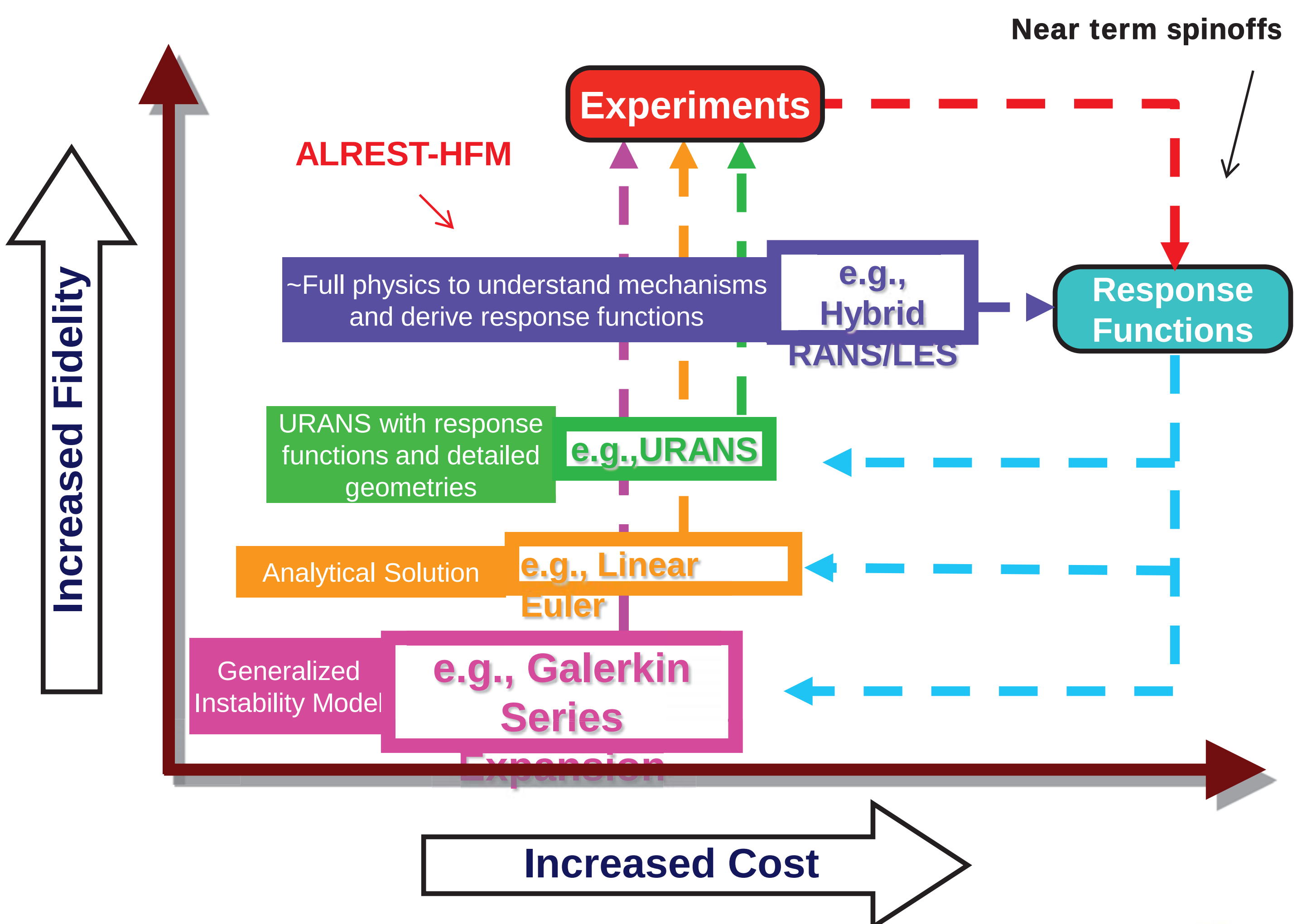
Menon (GA Tech)
- **ALREST, AFOSR**

Munipalli (HyPerComp)
- **ALREST**

Sirignano, Sideris (UC Irvine)
- **AFOSR**

Lynch (PWR)
- **ALREST**

Models

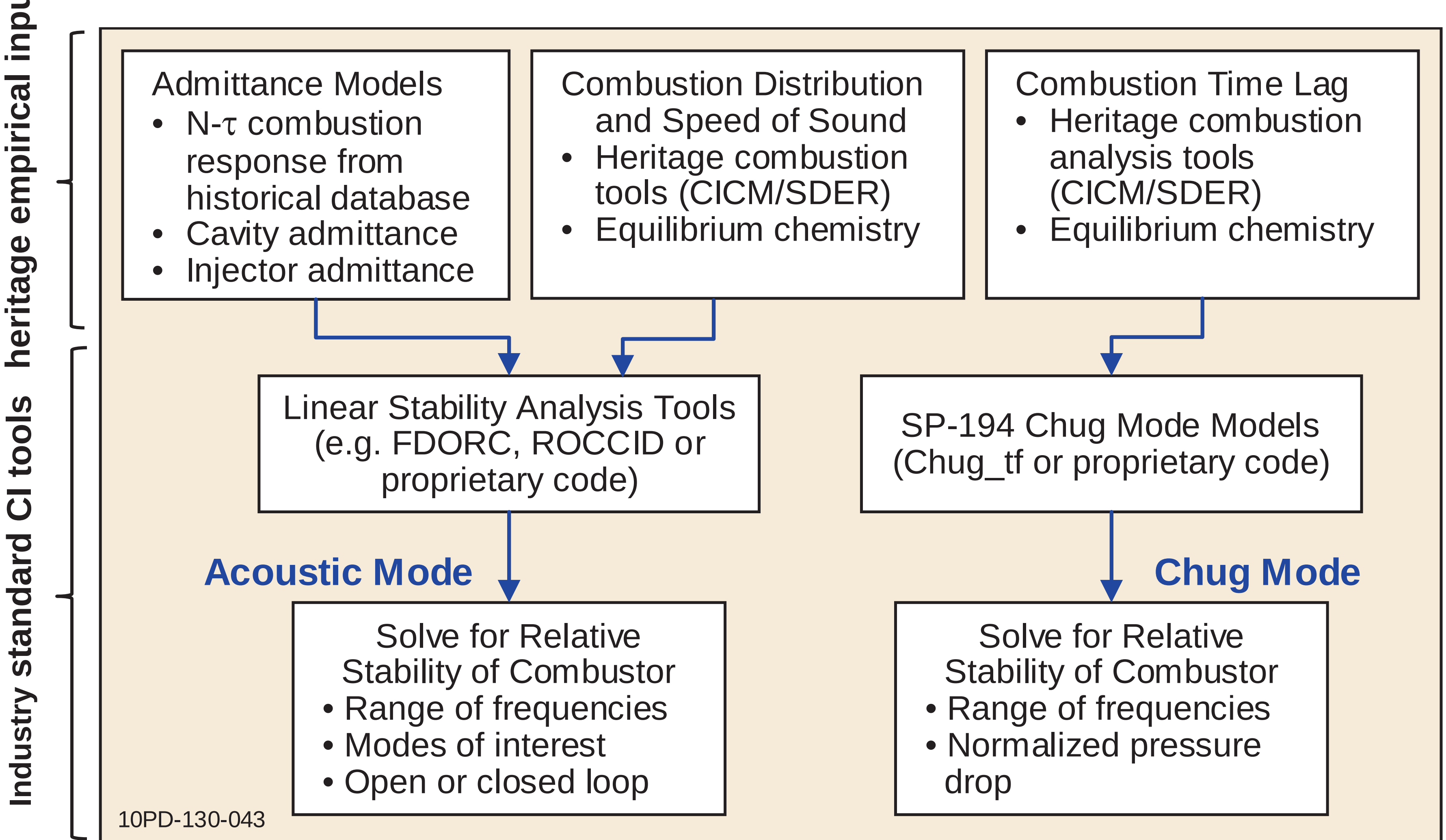


ALREST-HFM (AHFM)

- ALREST – High Fidelity Modeling is a six year program to develop high fidelity design tools for combustion stability
  - Central strategy is to take advantage of exponentially growing computational capability as our fastest growing enabling tool.
  - Two independent 3-year phases
    - Selection for phase I does not guarantee selection for phase II
- Tools will be validated against HCB data and applied to follow-on engine programs.

Combustion Stability Design Tools

Current



Combustion Stability Design Tools

End of phase I

ALREST-HFM 1.0
High fidelity CFD inputs, specifically:

- **Combustion distribution (speed of sound, T, P, time lag, etc.)**
- **Increase admittance accuracy**
- **Combustion response**

Industry standard CI tools

Linear Stability Analysis Tools (e.g. FDORC, ROCCID or proprietary code)

SP-194 Chug Mode Models (Chug_tf or proprietary code)

Acoustic Mode

Solve for Relative Stability of Combustor
- Range of frequencies
- Modes of interest
- Open or closed loop

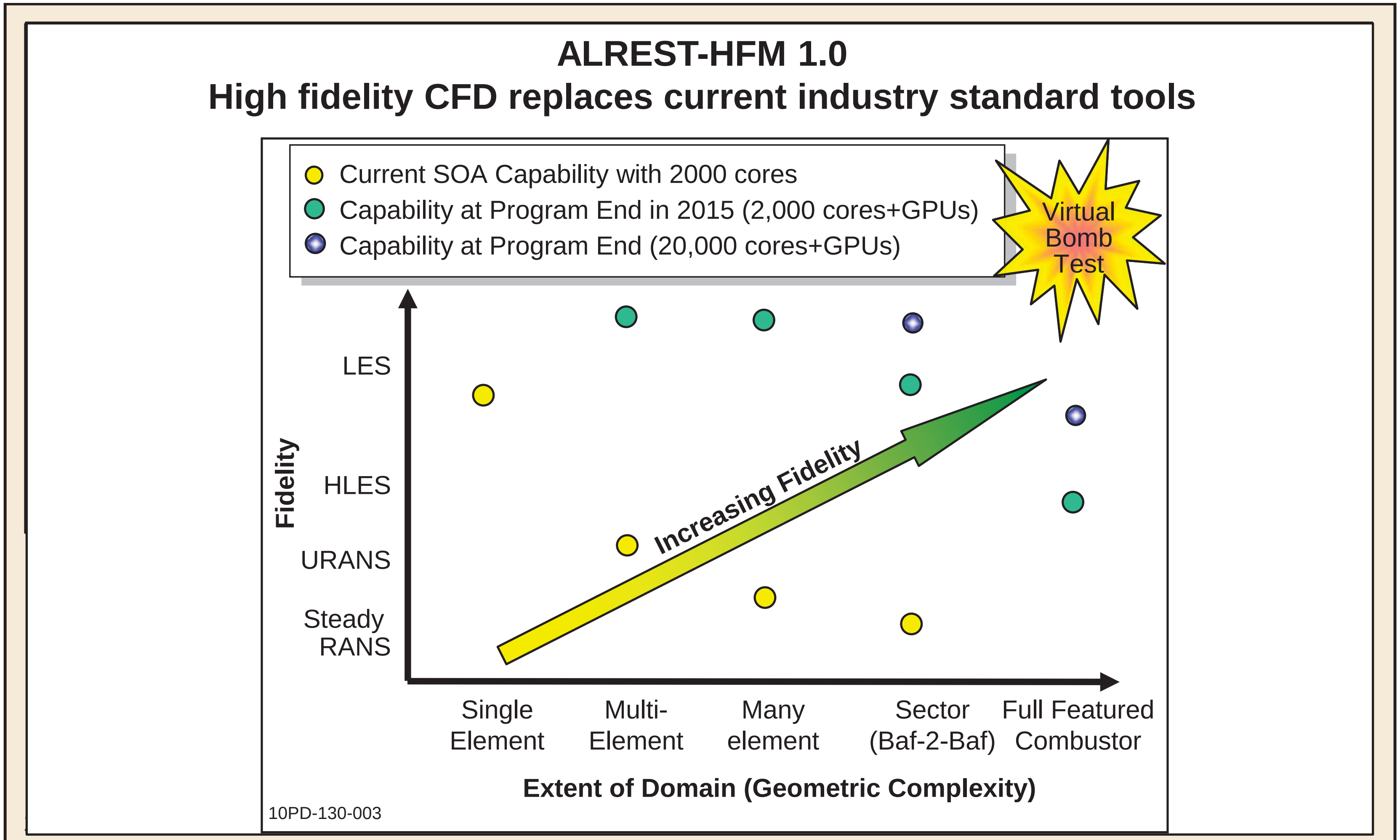
Chug Mode

Solve for Relative Stability of Combustor
- Range of frequencies
- Normalized pressure drop

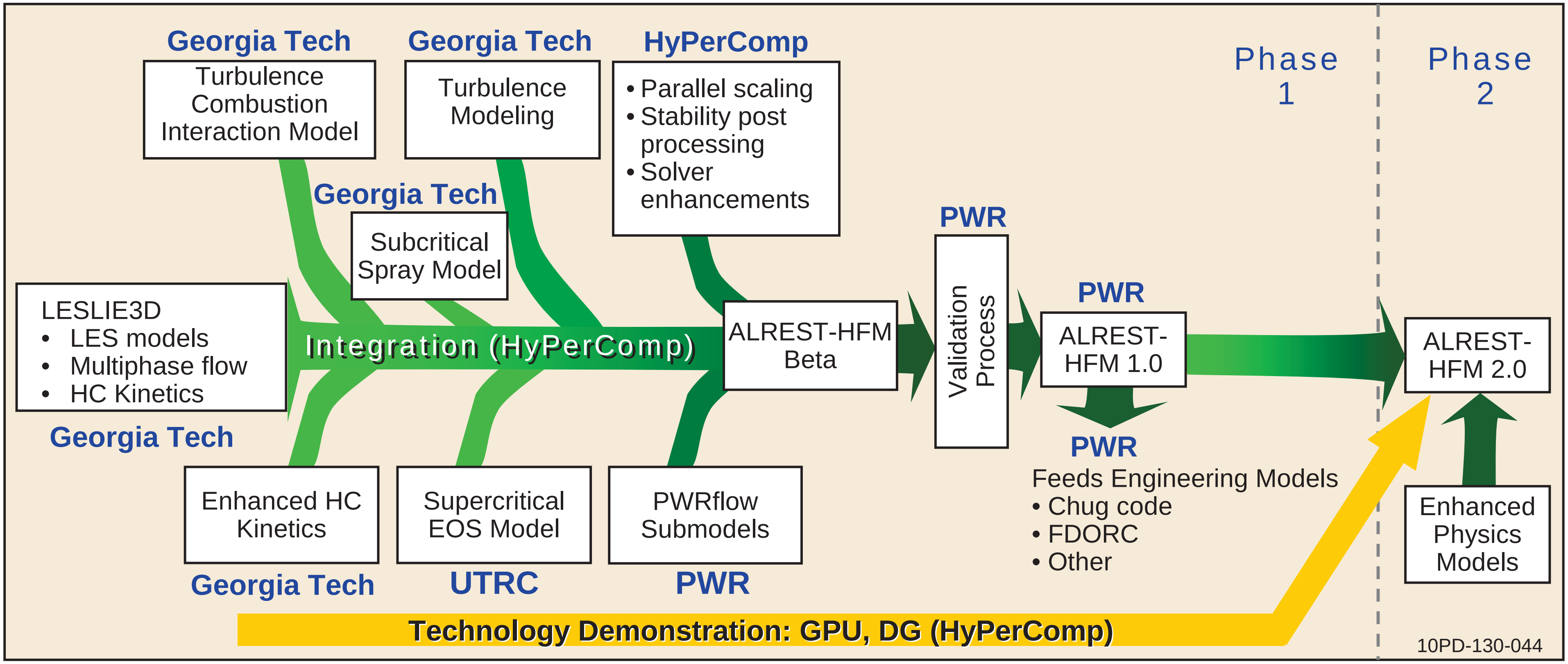
10PD-130-043

Combustion Stability Design Tools

Future vision



Approach



Source code will be delivered and maintained by Hypercomp after the contract ends

Marriage of PWR PWRflow RANS and Georgia Tech LESLIE3D Codes

	Discretization	Solution Advancement Schemes	Types of Grid	Turbulence Modeling	Kinetics Models	Fluid Properties	Turbulence-Chemistry Interaction Modeling	Discrete Multiphase Modeling	Dispersed Multiphase Modeling
LESLIE3D	Hybrid HLC/E	Currently Explicit Predictor-Corrector Temporal 2nd-Order	Structured; Structured-Unstructured Cartesian	Subgrid Scale K-KL and K-Δ	Variety of Hydrogen and Hydrocarbon Models for Gas Turbines, Ramjets, and LRE's	Mixtures of Calorically Perfect Gases and Mixtures of Peng-Robinson Fluids with Detailed Species Properties	Variety of RANS and LES modeling ranging from flamelets, eddy breakup modeling to LEM (Linear Eddy Modeling)	Detailed Level Set model for drop breakup with interface refinement	Lagrangian Droplet Model with drop breakup and evaporation exercised on gas turbine analyses
PWRflow	Cell-Based Limiting with Rusanov, Roe, and FORCE (large density differences) Riemann solvers	Diagonalized and Precond-itioned/Nonprec onditioned Point Implicit, Multigrid and Chunk G-S Global Implicit	Unstructured	Goldberg, Menter, and Spalart-Allmaras 1-Equation RANS Models; Anisotropic k- ε Model	1- and 2-step global, quasiglobal, and mechanistic models for a variety of hydrocarbons fuels and hydrogen including RP	Perfect Gas, Equilibrium Air, Mixtures of Calorically Perfect Gases and Mixtures of Redlich-Kwong and Peng-Robinson Fluids	Assumed pdf Model based on k-ε-g Model in NASA/LaRc Vulcan code	Level Set model for drop breakup employed on some selected problems	Lagrangian Droplet Model with breakup now being tested on gas turbine problems

AHFM Dev't Team

Program Manager
PWR
Brian Lariviere

Program Manager
AFRL
Doug Talley

Tech Advisors
PWR
Steve Barson CFD
Bob Jensen CA
Tim Hinerman CS

Principal Investigator
PWR
Doug Lynch

Tech Advisors
AFRL
Ananda Himansu
Venke Sankaran
Matt Harvezinski

Pratt & Whitney
A United Technologies Company

Georgia Tech College of Engineering

United Technologies Research Center

HyPerComp, Inc.
Leader in High Performance Computing

Task Lead
HyPerComp
Ramakanth Munipalli

- Code integration
- Scalability
- Validation
- Distribution/M&S

Task Lead
Georgia Tech
Suresh Menon

- L3D POD Code
- Sub-modelDev't
- Algorithm Dev't

Task Lead
UTRC
Dusty Davis

- Sub-models
- Physical Models
- Supercritical Fluid Properties

Tech Contributors
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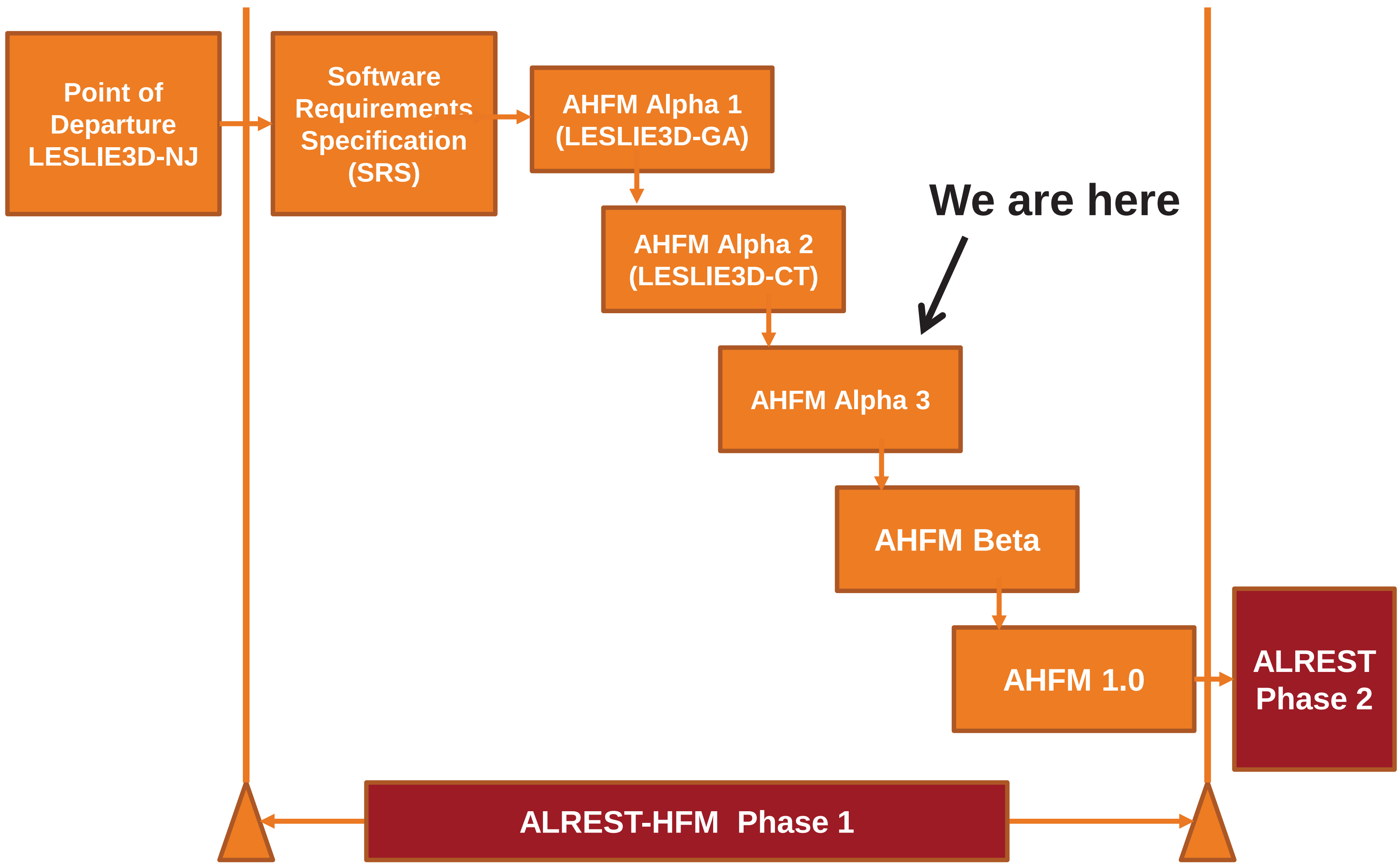
Tech Contributors
GT
Nicolas Guezennec
Matthieu Masquelet

Tech Contributors
UTRC
Jeremiah Lee

Four stages of development



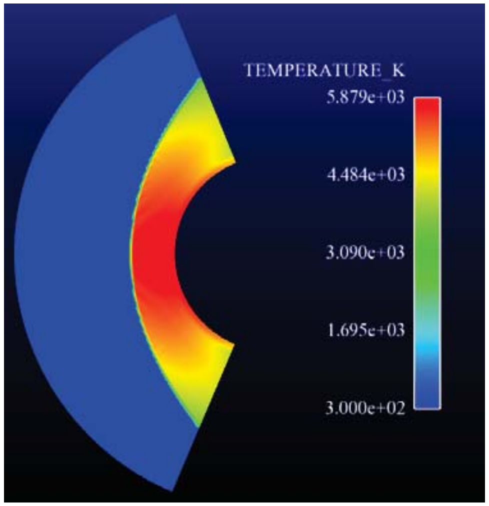
ALREST verification suite

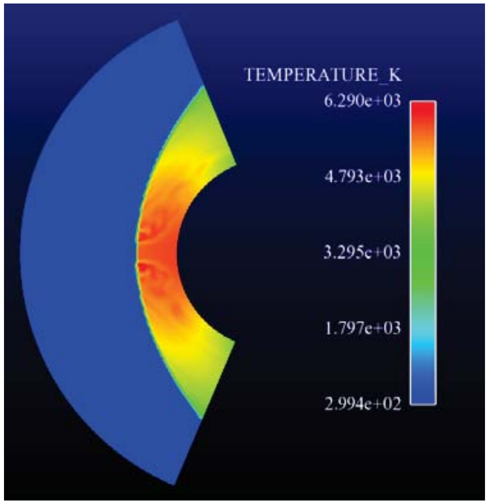
Case No.	Description of Test Case used for Verification
VR-1	**Uniform Flows (Run with all available schemes)**
VR-1.1	3D Uniform Flow in rotated uniform grid
VR-1.2	3D Uniform Flow in rotated non-uniform grid
VR-1.3	Uniform Flow in a 2-domain uniform grid
VR-2	**Simple Scaling Study**
VR-2.1	3D Temporal Mixing Layer (TML) with light load
VR-2.2	3D TML with normal load
VR-3	**Wave Propagation Accuracy**
VR-3.1	Quasi 1D Gaussian pressure pulse traveling in a duct of variable area
VR-3.2	Above with temperature variation
VR-4	**Flame Test Cases**
VR-4.1	Laminar premixed methane/air flame (phi=1,p=1 to 60 atm, 4-step, 8-species, initial solution from GRI)
VR-4.2	Laminar premixed H2/Air flame (phi=0.7)
VR-5	**Boundary Condition Test Cases**
VR-5.1	Pressure reflection from inflow, non-reflecting exit at outflow
VR-5.2	Above with turbulent inflow
VR-5.3	Above with Calorically (CPG) vs Thermally (TPG) perfect gas models
VR-6	**Convection Test Cases**
VR-6.1	1D Tests of wave speed with jump in species concentration
VR-6.2	1D Shock tube problem with limiters and artificial dissipation
VR-6.3	1D Gaussian pulse with different flux formulae
VR-6.4	2D convected vortex
VR-6.5	1D Gaussial entropy wave
VR-7	**Temporal Mixing Layer**
VR-7.1	3D, 1 species Euler CPG mixing layer model
VR-7.2	2D, 2 species CPG model
VR-7.3	Shock Wave Test Cases
VR-7.4	1D Sod shock tube test case
VR-7.5	2D Oblique shock Mach 5, 25 deg wedge
VR-7.6	2D Richtmyer-Meshkov Instability

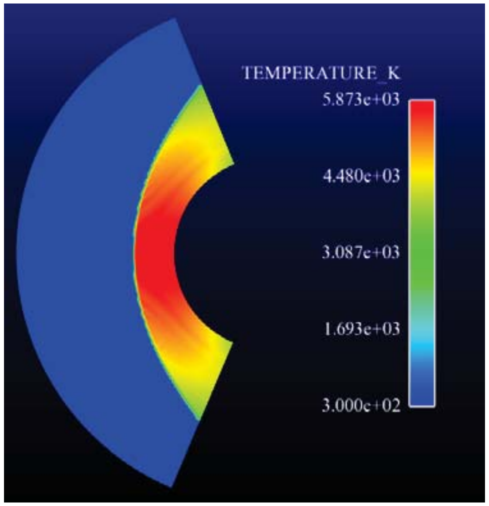
These are the set of "automated test cases" used to verify code integrity was maintained during code dev't

Two of the many verification cases

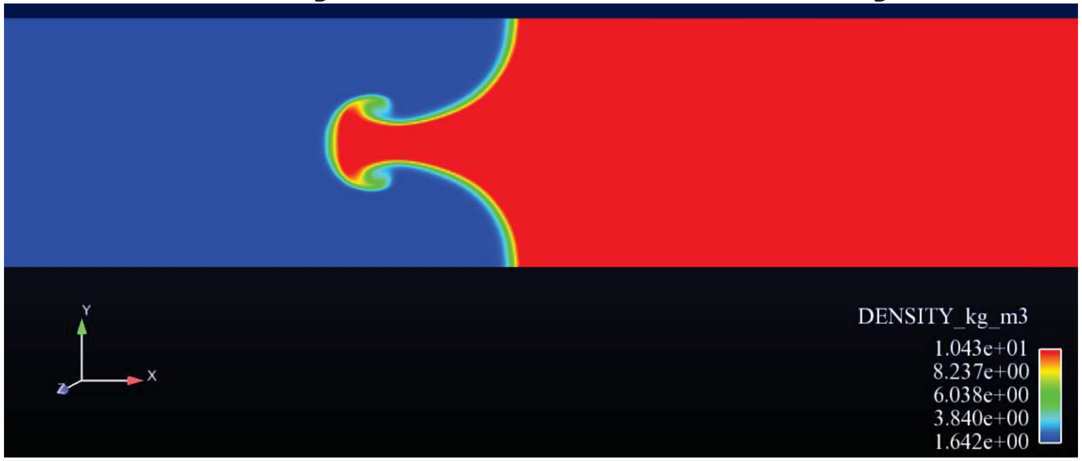
2D blunt body



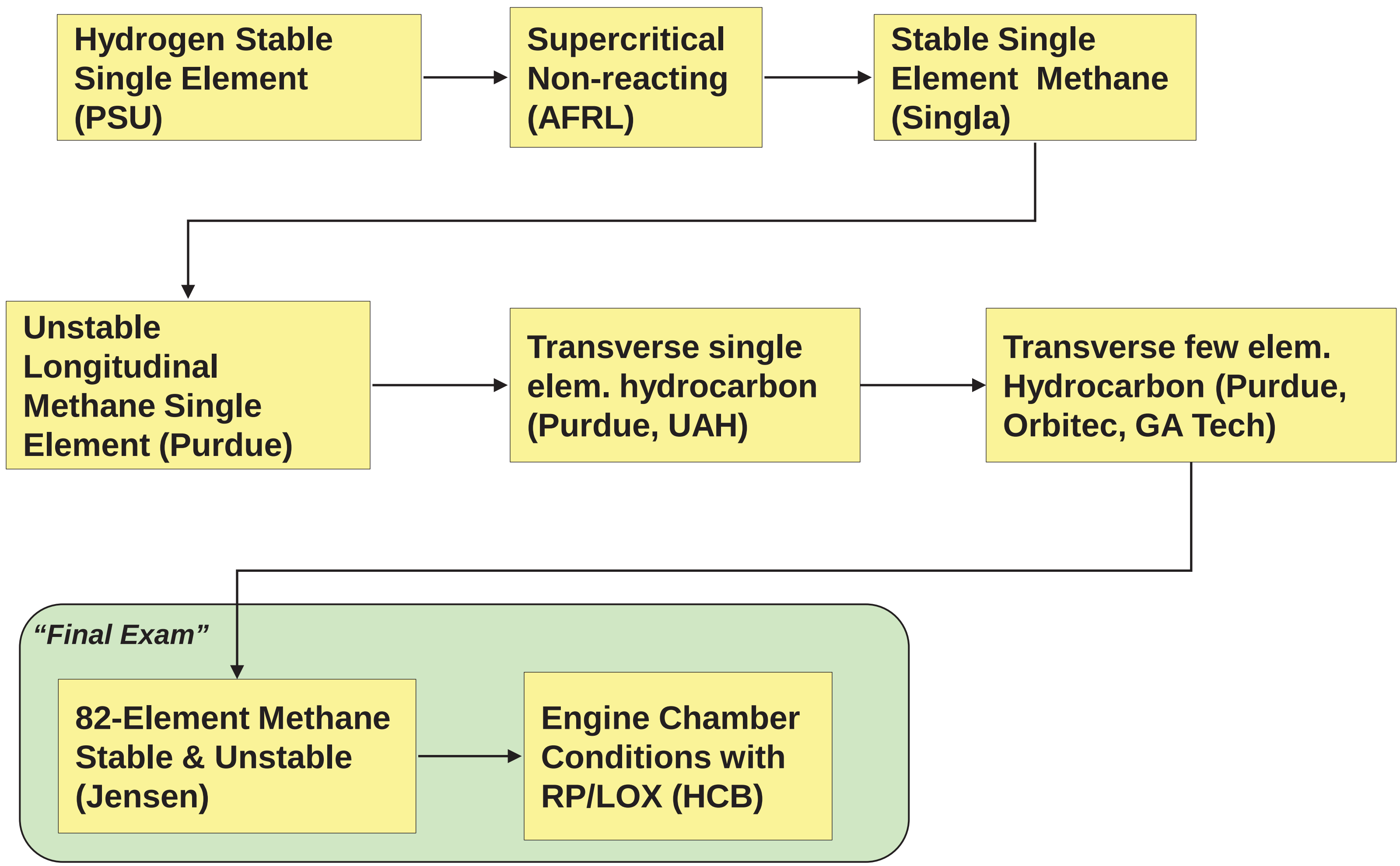




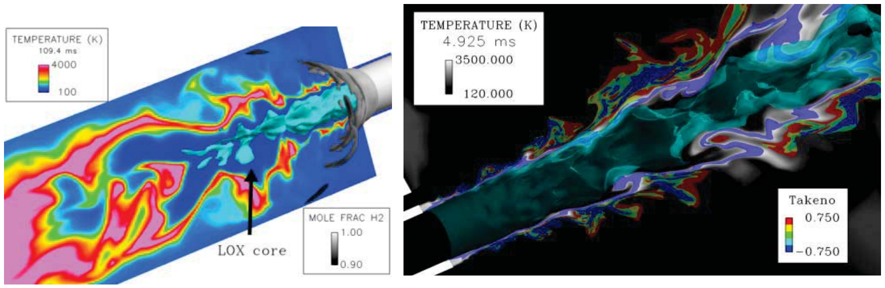
Richtmyer-Meshkov Instability



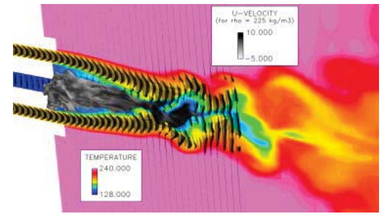
ALREST Validation Cases



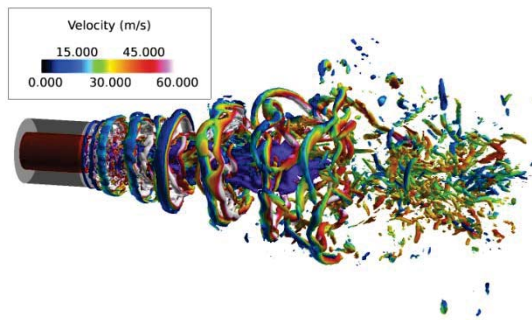
Validation Simulations

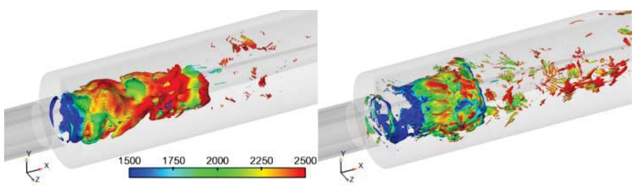


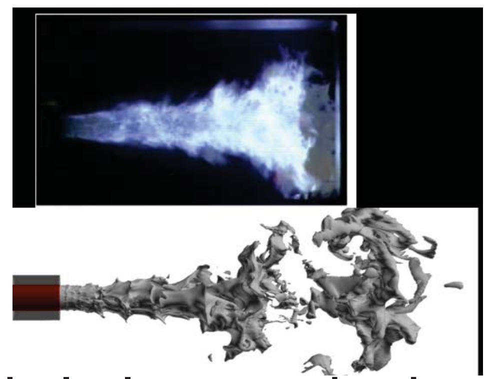
PSU LOX/H2 validation (NASA – leveraged)



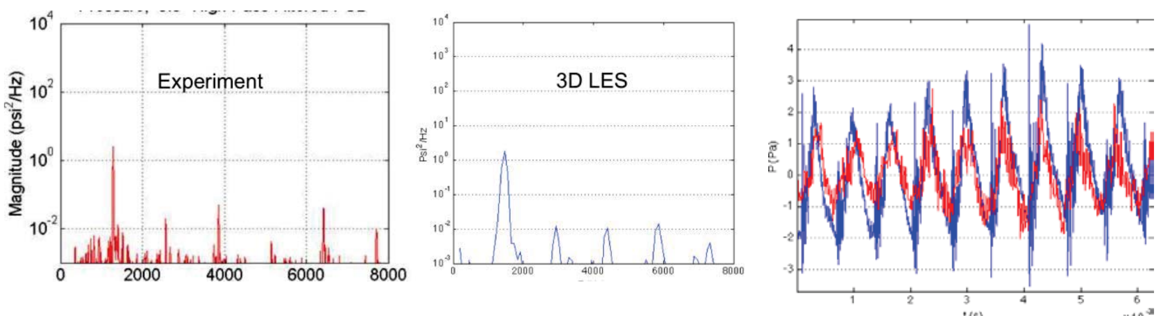
AFRL supercritical data (validation case)



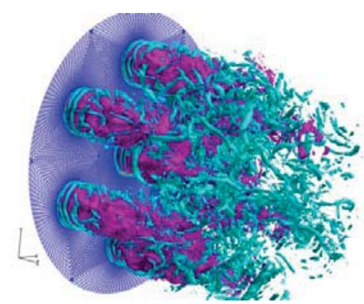




Single element combustion case



Purdue longitudinal validation case



7 element scalability study

AHFM Validation Case:
Case 3: CVRC Longitudinal Instability (Yu, et al)

Case Description:

- Case 3: Longitudinal Instability for Single Injector
- Yu et al Completed for Anderson CUIP Task
- Continuous Variable Resonance Combustor
- Oxidizer Post length=

Relevance to AHFM:

- Longitudinal Instability for Hydrocarbon Combustion under Supercritical Conditions

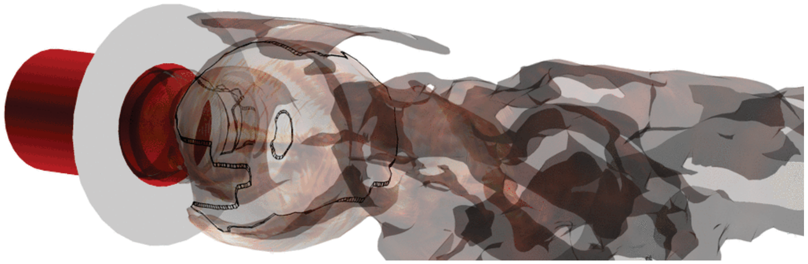
Key Metric or Success Criteria:

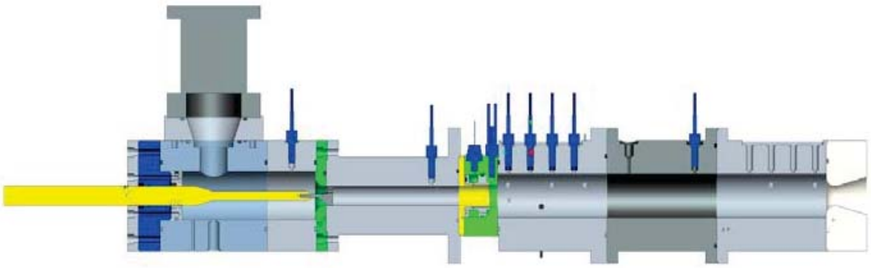
- Frequency and Amplitude Growth of Fundamental Instability and Higher Harmonic/Secondary Modes
- Mode Shapes and Phase

Status:

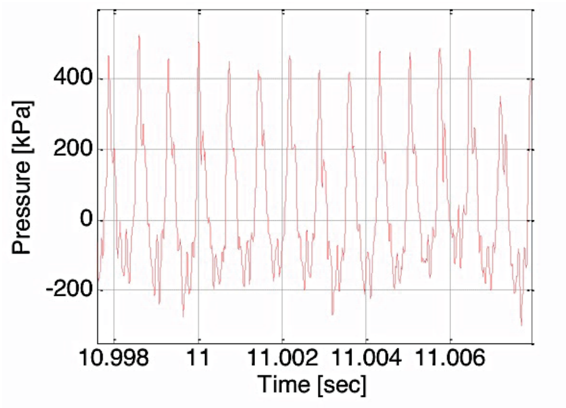
Complete; Analyzing Results
Code Version: AHFM-α1 (LESLIE3D-GA)
Computer System & No. of Cores
Grid Size:
Other Special Characteristics:

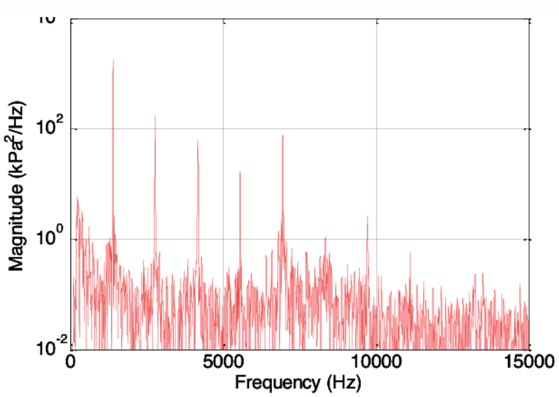
- Mixture of Calorically Perfect Gases
- xx Methane – Oxygen Kinetics



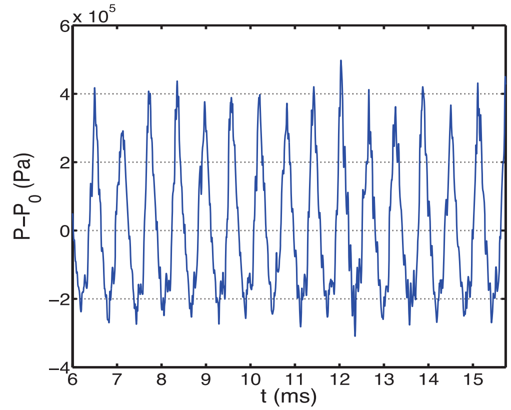


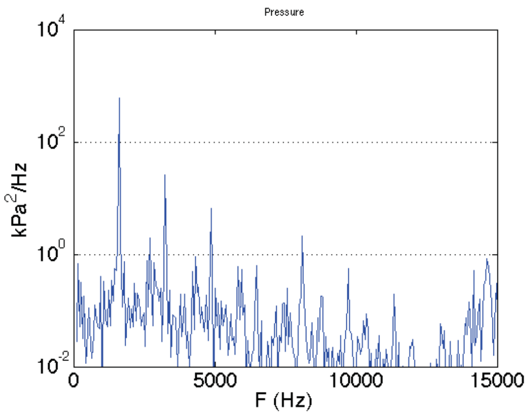
Pressure signal





Experiment





LESLIE

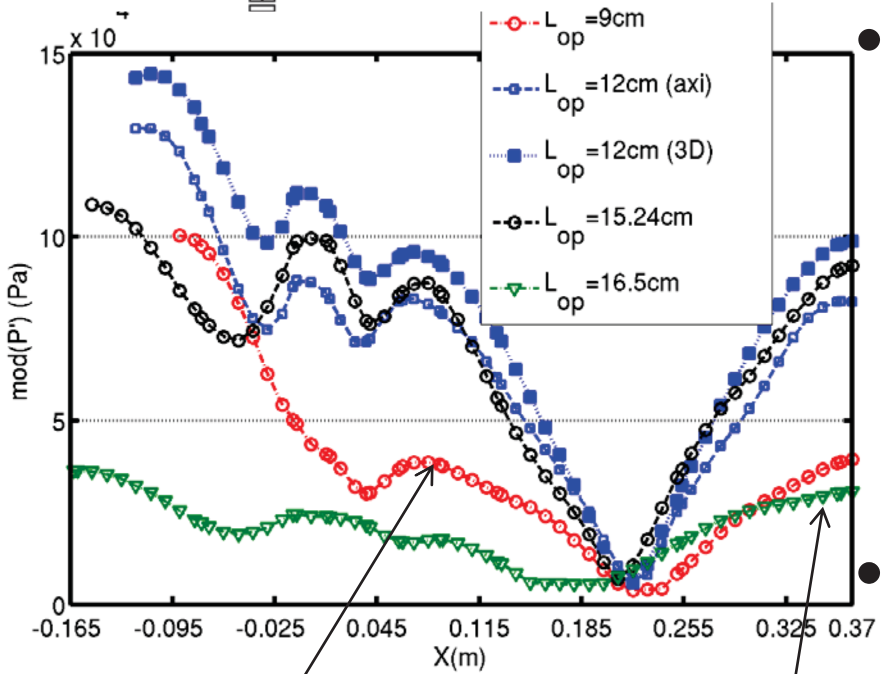
- Good prediction of the peak to peak fluctuations
- Good prediction of trends
- Frequency and amplitude slightly off
  - 200 Hz and x2 respectively
  - Reason still under investigation
- P_0=1.55 Mpa > P_{exp}=1.4 MPa

36.85 cm

Georgia Tech College of Engineering

Parametric study with Axi-LES

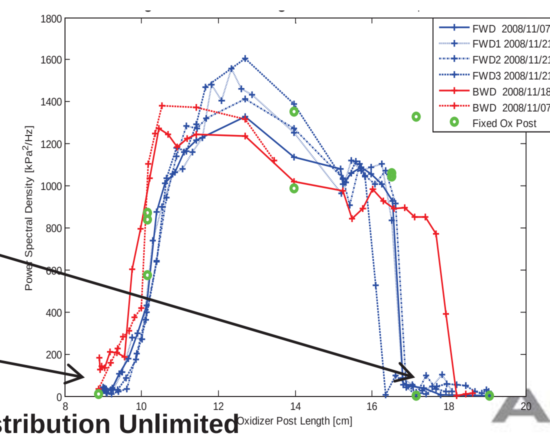
Georgia Tech College of Engineering



- Good prediction of the stability domain:
  - L<9cm and L>16cm: **strong reduction of acoustics**
  - L>9cm and L<16cm: **unstable combustor**
- Underestimation of the amplitude

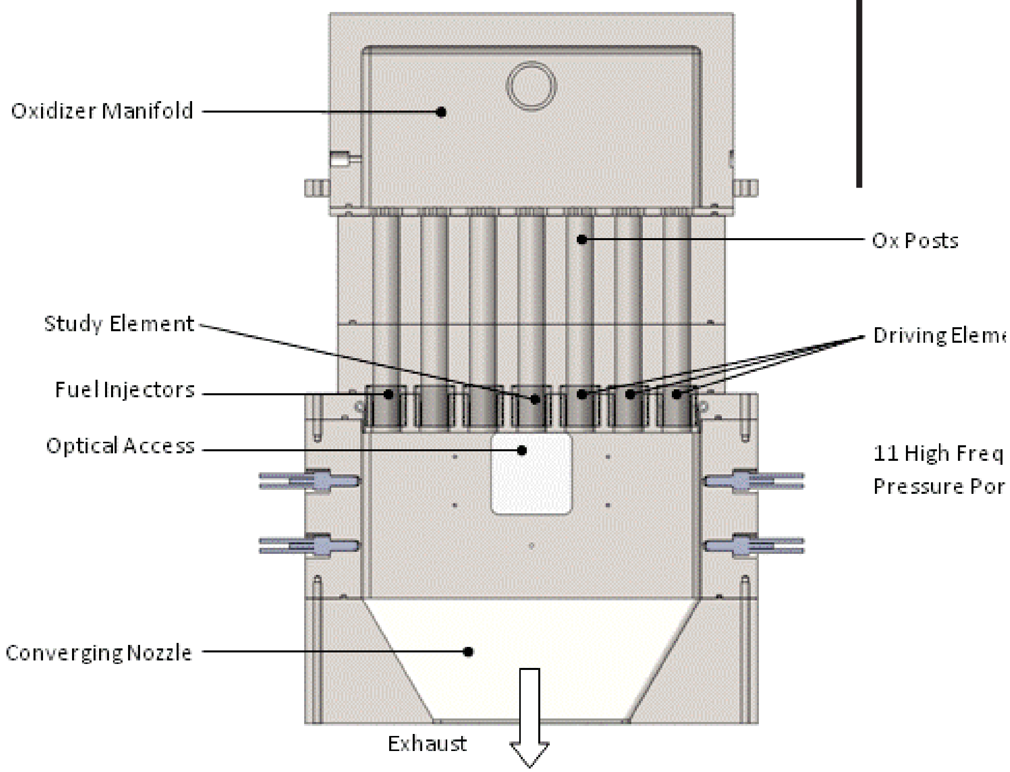
9 cm

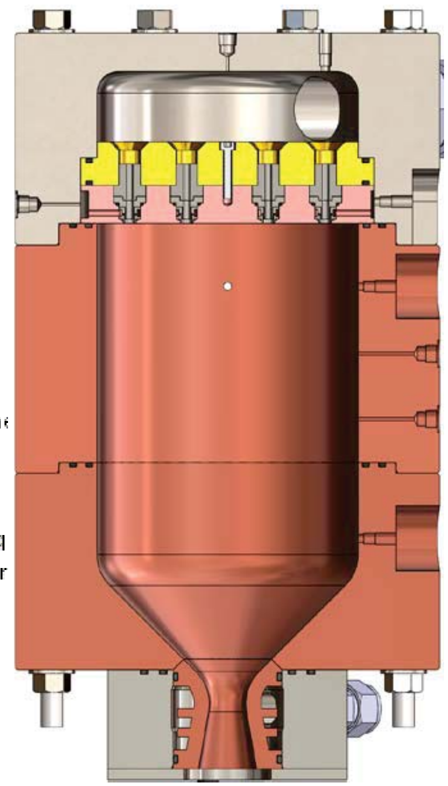
16 cm



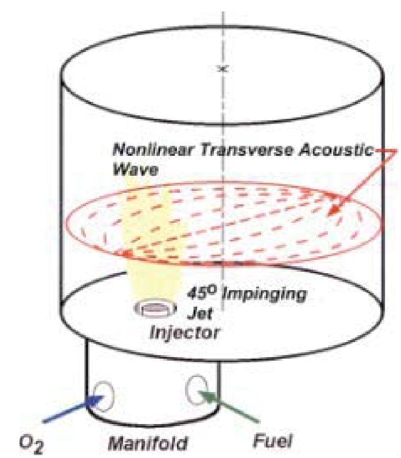
- Effect of the injector length on the combustor stability

Several-element transverse validation data will come from two phase II SBIRs



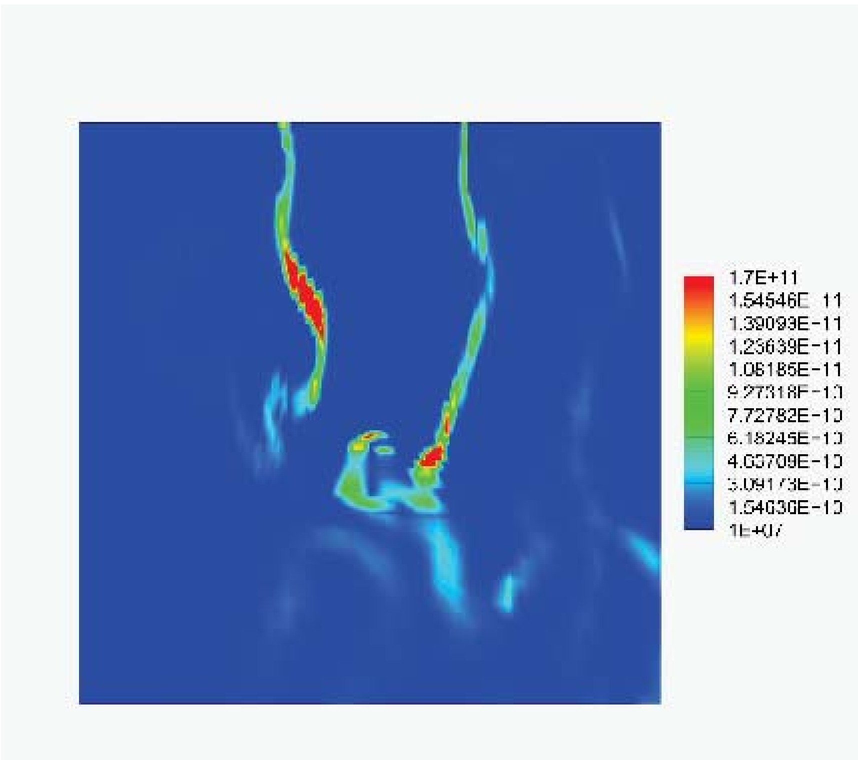


Scaling

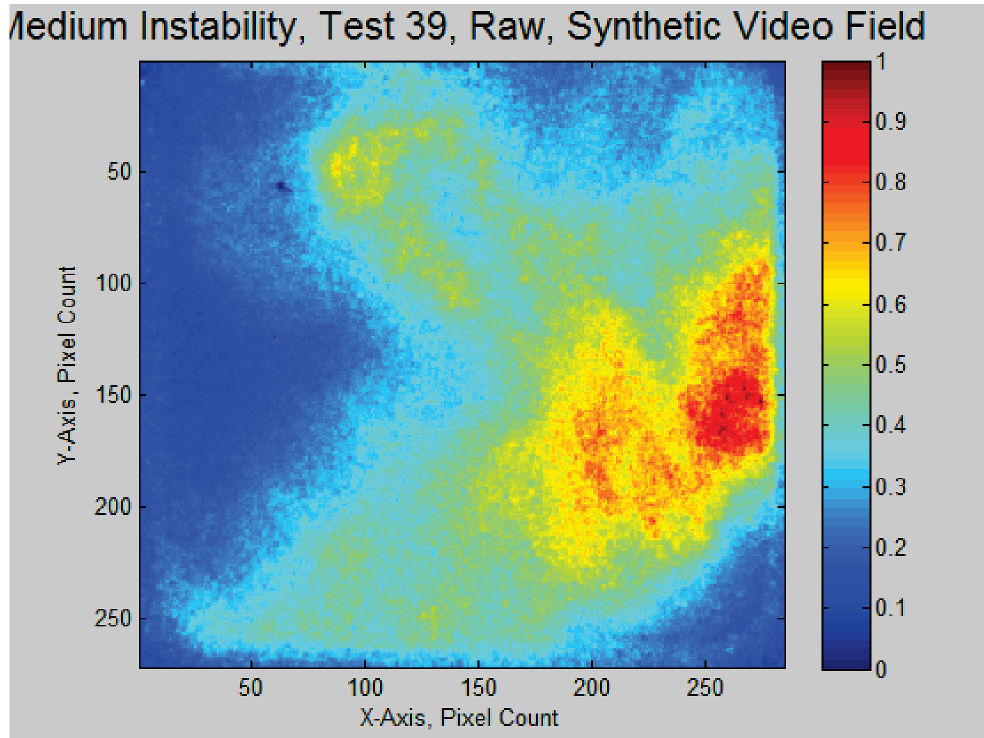


Heat Release

CFD Heat Rate (Watts)



Experiment Video - CH*



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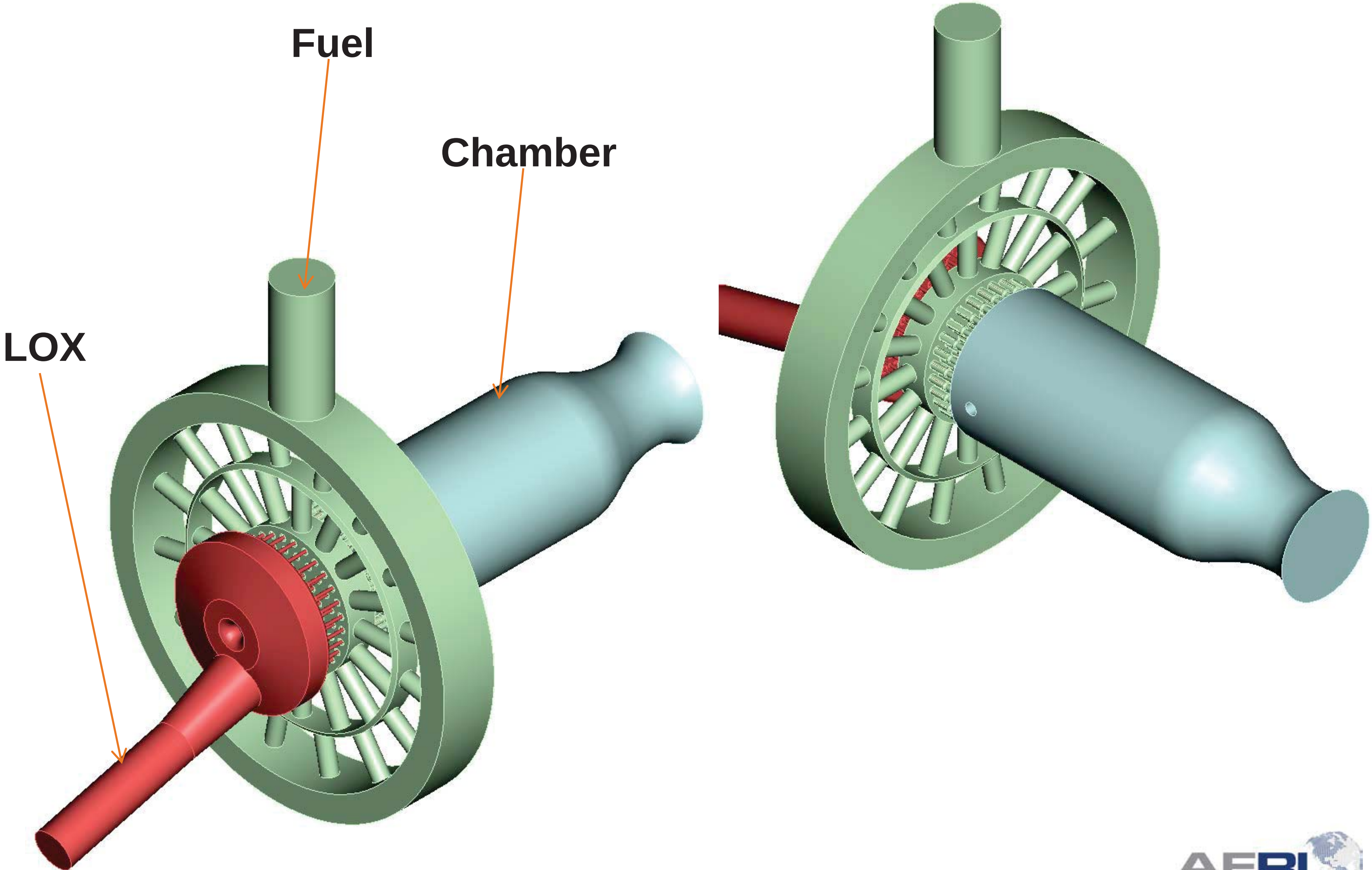
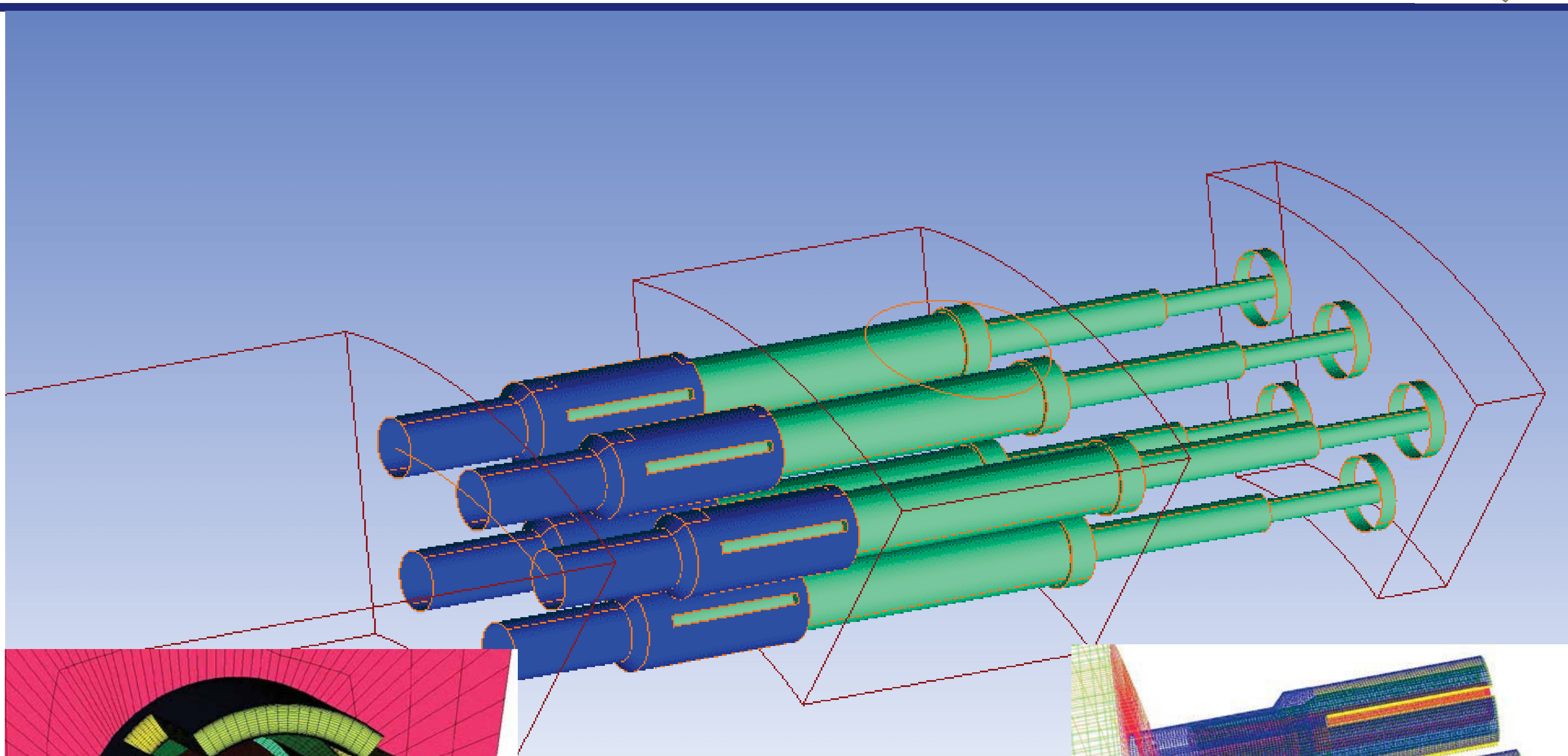
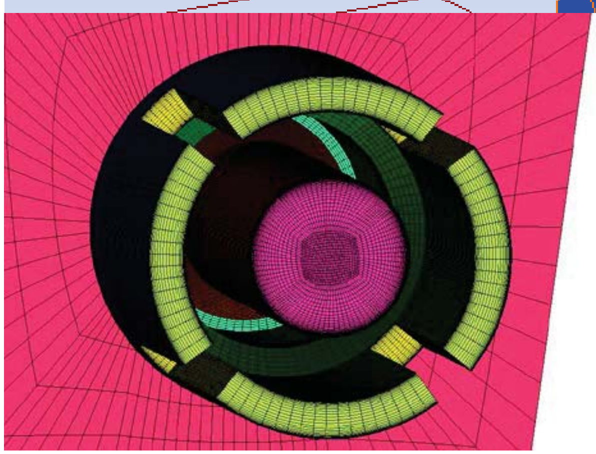
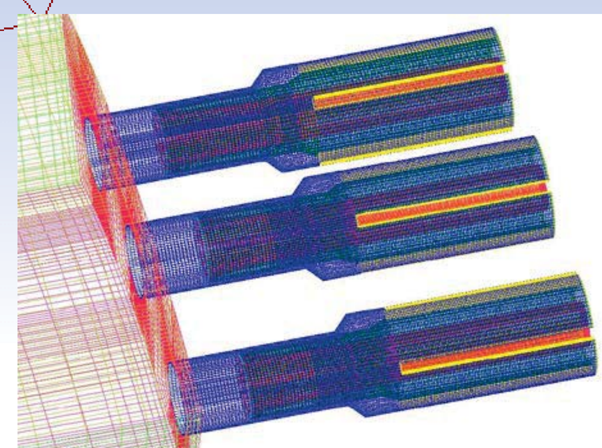
CAD drawing of engine and manifolds



Five Element Sector Mesh







Analytical Methods

Gloyer-Taylor Labs' UCDS suite of tools applied to existing liquid rocket engine data.

$$\frac{dR_m}{dt} = \alpha_m R_m; \quad \alpha_m = \left\{ \begin{array}{l} \underbrace{\frac{1}{2E_m^2} \iint_{S_{inj}} M_{inj}\left(A_{inj}^{(r)}+1\right)\psi_m^2 dS}_{\text{Pressure Coupling}} - \underbrace{\frac{1}{2E_m^2} \iint_{S_N} M_{inj}\left(A_N^{(r)}+1\right)\psi_m^2 dS}_{\text{Nozzle Damping}} \\ + \underbrace{\frac{1}{2E_m^2} \iint_{S_{inj\|}} M_{inj}\left(B_{inj}^{(r)}\right)\psi_m^2 dS}_{\text{Acoustic Boundary Layer Pumping (ABL)}} - \underbrace{\frac{1}{2E_m^2} \iint_{S_{inj\|}} \left(\frac{\delta}{2\gamma M_{inj}}\right)^2 \left(\nabla\psi_m \cdot \nabla\psi_m\right) dS}_{\text{Viscous Damping at Injection Surfaces}} \\ \underbrace{- \frac{1}{2\gamma P_0 E_m^2} \iiint_V \rho_0 \mathbf{u}_0 \cdot \langle \mathbf{u}_1 \times \omega_1 \rangle dV - \frac{1}{2\gamma P_0 E_m^2} \iiint_V \rho_1 \mathbf{u}_1 \cdot \langle \mathbf{u}_0 \times \omega_0 \rangle dV}_{\text{Vortex Shedding Effects; Flow-Turning Damping}} \\ + \underbrace{\frac{1}{2\gamma P_0 E_m^2} \iiint_V \left\langle \frac{\mathscr{H}_1 T_1}{T_0} - \frac{\mathscr{H}_0 T_1^2}{T_0^2} \right\rangle dV}_{\text{Distributed Combustion; Heat Release}} + \left\{ \begin{array}{l} (\text{Viscous Losses; Energy Dissipation}) \\ +(\text{Heat Transfer}) \\ + \left(\begin{array}{l} \text{Particle Damping and} \\ \text{Other Two} - \text{Phase Flow Effects} \end{array} \right) \end{array} \right\} \end{array} \right\}$$

Summary

- **ALREST**
  - Nationally coordinated data-centric multi-fidelity model development
  - ALREST-HFM is the high-fidelity physics-based platform
  - Validated using relevant rocket data
  - Results are input into lower-fidelity engineering tools
- **Future**
  - More sophisticated physics models
  - Improved combustion diagnostics
  - Modular code and model development
  - Reduced-basis model development